Adaptive Computational Fluid Dynamics: Petascale and Beyond

K.E. Jansen
Aerospace Engineering Sciences
University of Colorado at Boulder

C. Carothers, O. Sahni, M.S. Shephard

Scientific Computation Research Center
Rensselaer Polytechnic Institute
Department of Mechanical, Aerospace and Nuclear Engineering and Computer Science

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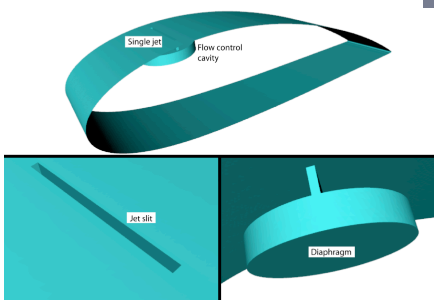
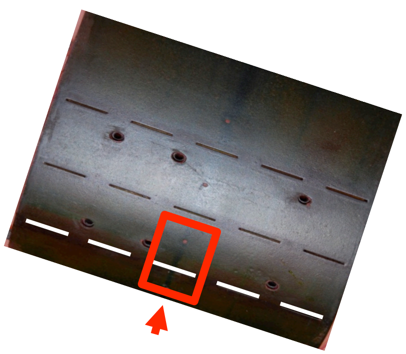
Outline

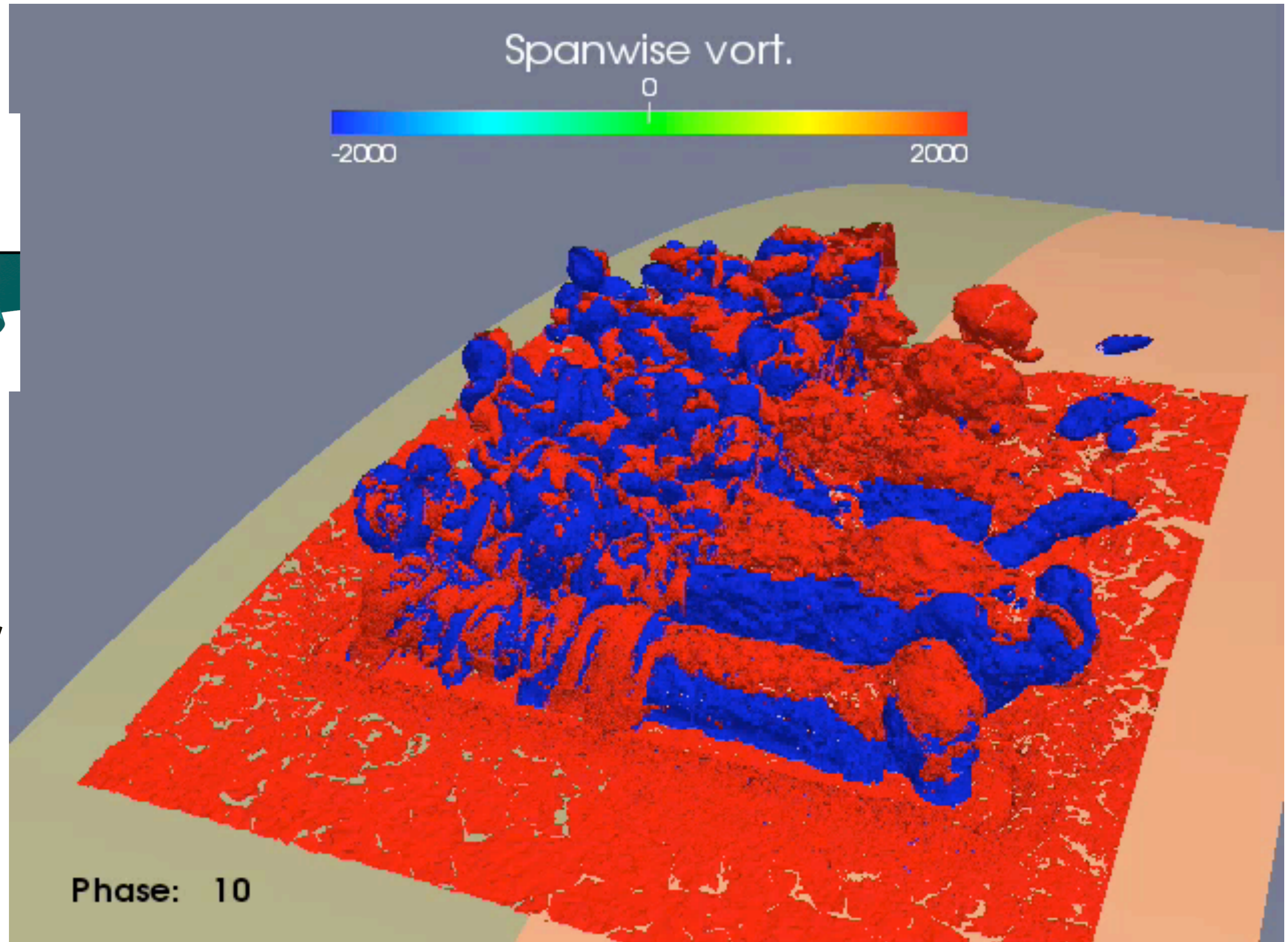
- Background and Motivation
- Petascale Flow Solver
- Current Scaling Results
- Applications
- Conclusions

Problems of Interest

Aerodynamic Flow Control

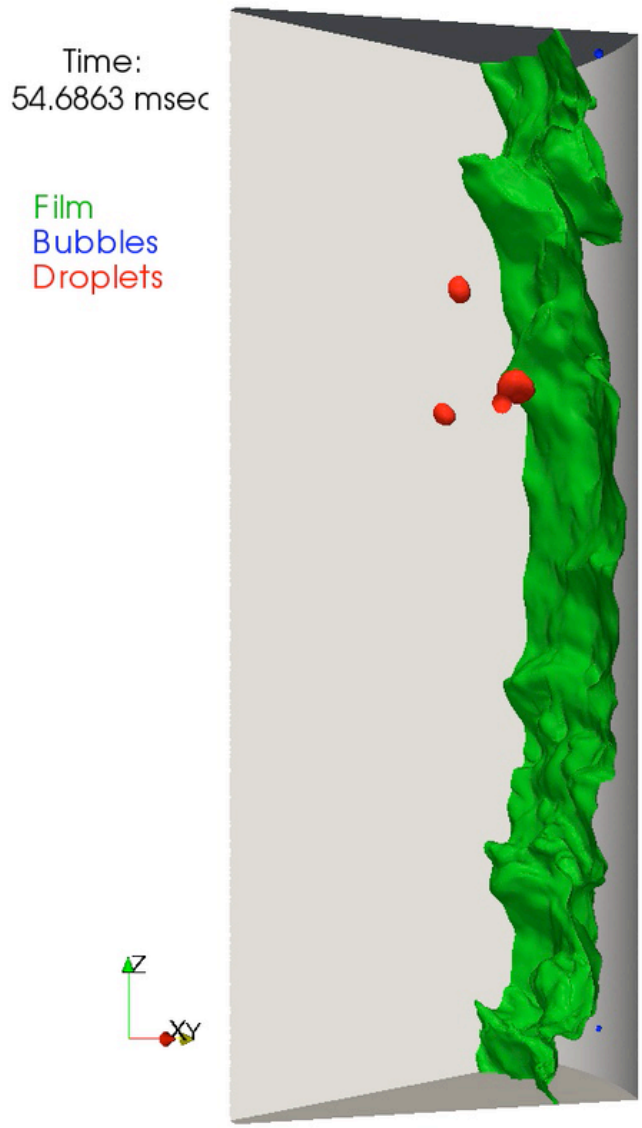




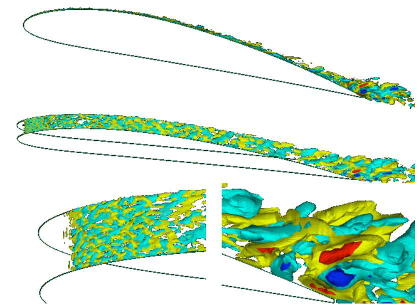


Problems of Interest

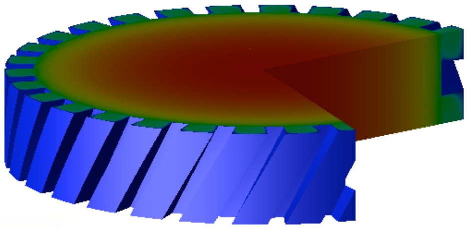
Two-phase
Annular Flow

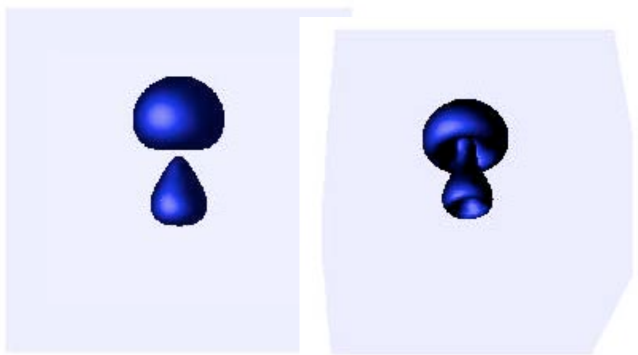


PHASTA Models



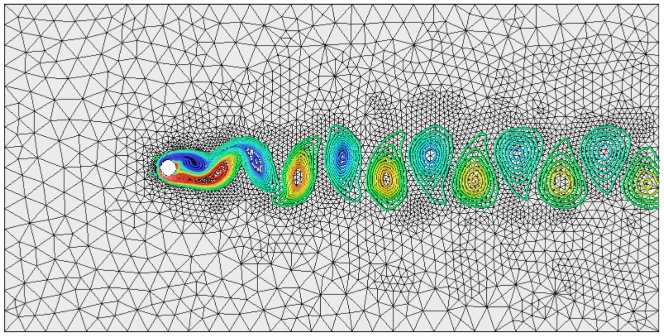
- Compressible or Incompressible Fluid Flow
- Turbulence
  - Direct Numerical Simulation (DNS)
  - Large-Eddy Simulation (LES)
  - Reynolds-Averaged Navier-Stokes (RANSS)
  - Detached Eddy Simulation (DES) and other hybrid models
- History
  - Stanford (ENSA)
    - Euler 1985, Laminar NS 1988,
    - RANS 1991
  - CTR (Stanford-Ames)
    - Parallel LES 1994
  - RPI (ENSA evolves to PHASTA)
    - Parallel DES 2000,
    - Adaptivity 2002
    - Level set multiphase 2003
    - Parallel adaptivity 2006

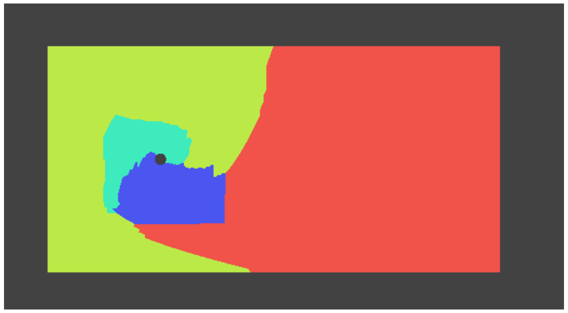




PHASTA Flow Solver

- Stability with Accuracy
  - Hierarchic spatial basis (currently p<4) $O(h^{p+1})$
  - Stabilized finite element method
  - Combined, yield accurate, well controlled, stabilization
  - Time integration: explicit (4th order RK) and implicit (2nd order generalized alpha method).
- Adaptivity
  - Grid matches physical scale
  - Anisotropic and transient
- Parallel
  - Excellent scaling to 288k processors
- Parallel Hierarchic Adaptive Stabilized
- Transient Analysis





Current Approach – NS Flow Solver

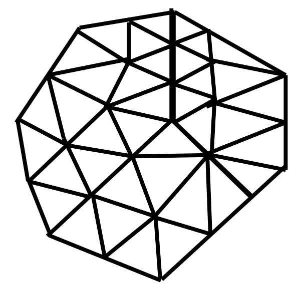
- Implicit non-linear FEM solver with two phases of computation:
  - **Equation formation** (*Eqn. form.*) – depends on *elements*

PDE/strong form – $\mathscr{L}\boldsymbol{Y} = \mathscr{S}$

Weak form – $\int_{\Omega} (\dot{}) \, \mathrm{d}\Omega + \int_{\Gamma} (\dot{}) \, \mathrm{d}\Gamma$

Quadrature – $\boxed{\overset{vol}{\sum} (\dot{}) + \overset{bdy}{\sum} (\dot{})}$

Assembly – $\mathrm{A}\mathrm{x} = \mathrm{b}$



  - **Equation solution** (*Eqn. sol.*) – depends on *degrees-of-freedom* (*dofs*):

$\mathrm{A}\mathrm{x} = \mathrm{b}$

Iterative solver

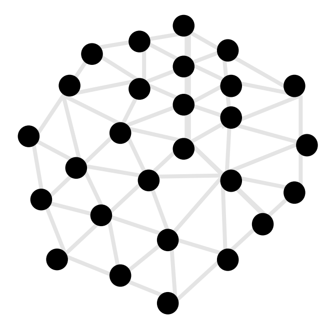
$\mathrm{p} = \mathrm{b}$

while

$\boxed{\mathrm{q} = \mathrm{A}\mathrm{p}}$

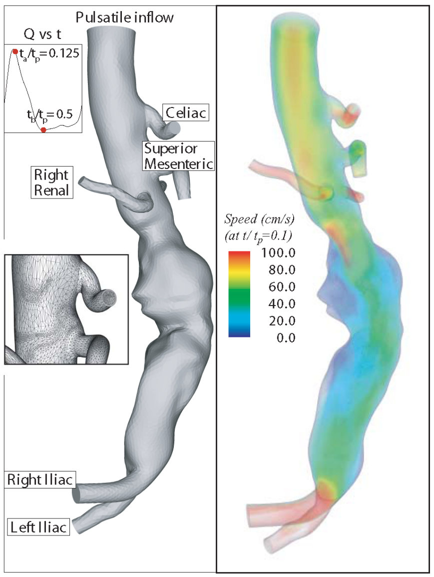
Orthonormalize q

...



Strong Scaling – 1B Mesh up to 160k Cores

- AAA 1B elements: ***extreme scale*** (full-system)



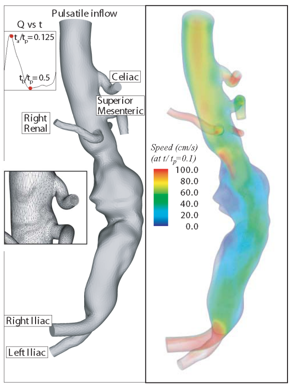
1.07B elements mesh (Intrepid:IBM BG/P)		Total	
num. of core	avg. elem./core	time	s-factor
4,096 (base, 1 rack)	261,600	844.92	1
8,192; 16,384; 32,768			
65,536 (16 racks)	16,350	58.29	0.91
98,304 (24 racks)	10,900	39.98	0.88
131,072 (32 racks)	8,175	31.02	0.85
163,840 (all 40 racks)	6,540	25.61	0.82

Eqn. form	
time	s-factor
388.68	1
24.59	0.99
16.42	0.99
12.37	0.98
10.27	0.95

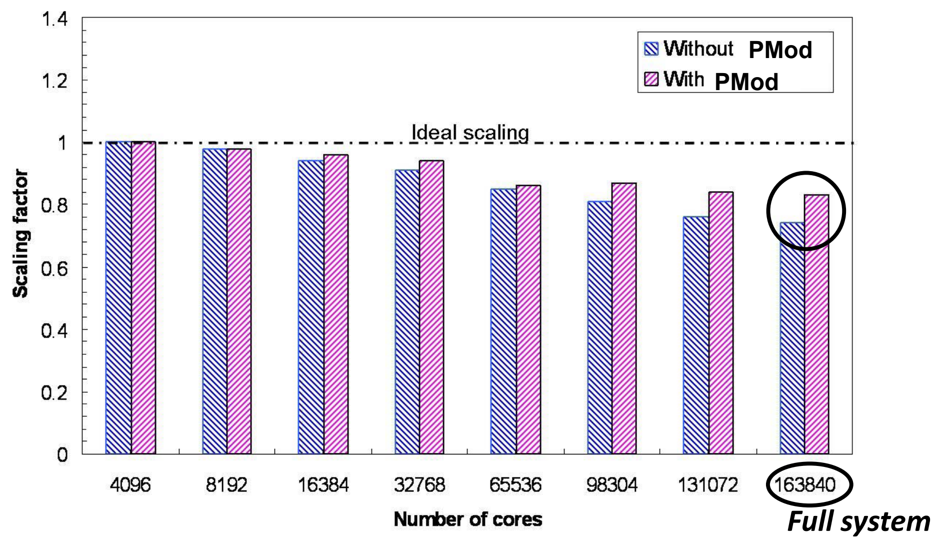
Eqn. soln	
time	s-factor
456.24	1
33.70	0.85
23.56	0.81
18.65	0.76
15.34	0.74

Strong Scaling – 1B Mesh up to 160k Cores

- AAA 1B elements: ***effective partitioning*** at extreme scale
  with and without partition modification (IPMod)



1.07B elements mesh (Intrepid:IBM BG/P)	
num. of core	avg. elem./core
4,096 (base, 1 rack)	261,600
8,192; 16,384; 32,768	(see graph)
65,536 (16 racks)	16,350
98,304 (24 racks)	10,900
131,072 (32 racks)	8,175
163,840 (all 40 racks)	6,540



Without IPMod

Eqn. form.	
time	s-factor
388.68	1
24.59	0.99
16.42	0.99
12.37	0.98
10.27	0.95

Eqn. soln.	
time	s-factor
456.24	1
33.70	0.85
23.56	0.81
18.65	0.76
15.34	0.74

Total	
time	s-factor
844.92	1
58.29	0.91
39.98	0.88
31.02	0.85
25.61	0.82

with IPMod

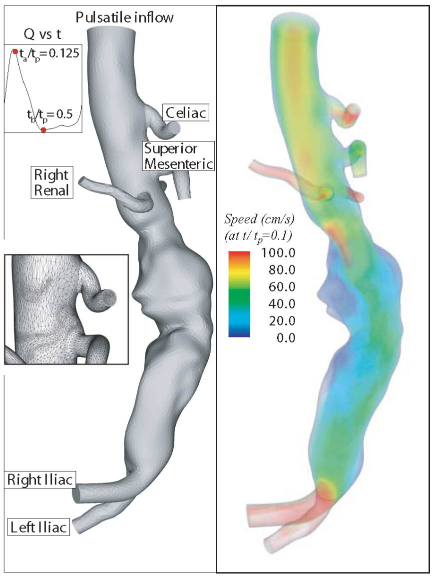
Eqn. form.	
time	s-factor
388.90	1
25.48	0.95
17.12	0.95
12.79	0.95
10.46	0.93

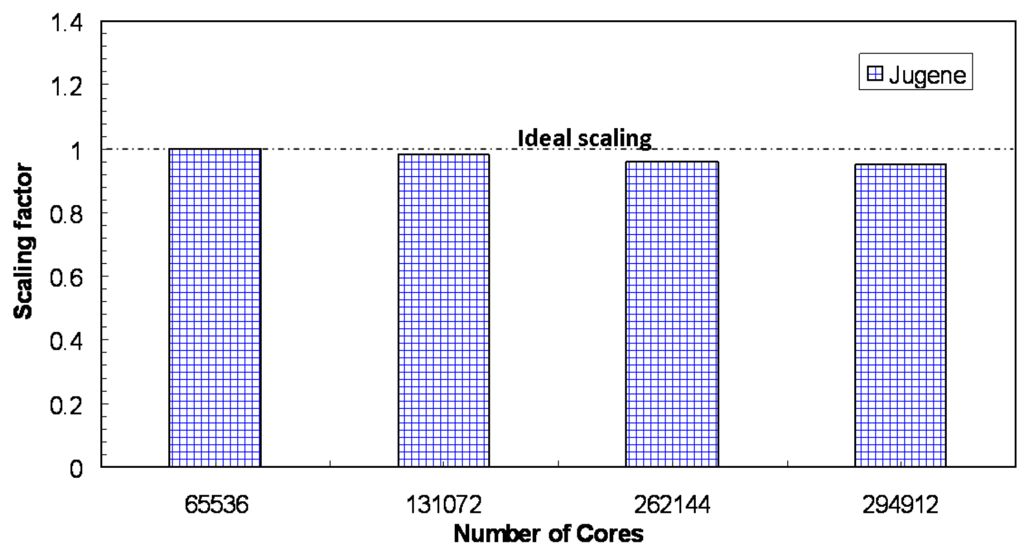
Eqn. soln.	
time	s-factor
455.48	1
33.17	0.86
21.94	0.87
16.89	0.84
13.66	0.83

Total	
time	s-factor
844.38	1
58.65	0.91
39.06	0.90
29.68	0.89
24.12	0.88

Strong Scaling – 5B Mesh up to 288k Cores

- AAA 5B elements: full-system scale on Jugene (IBM BG/P system)



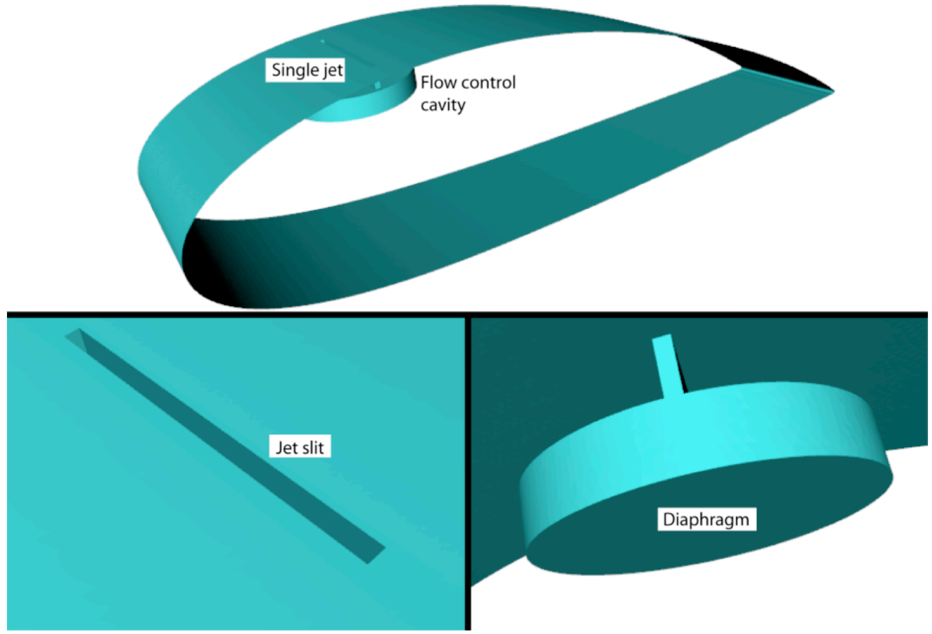


5B elements mesh (Jugene:IBM BG/P)		Eqn. form.		Eqn. soln.		Total	
num. of core	avg. elem./core	time	s-factor	time	s-factor	time	s-factor
65,536 (base)	76,480	119.64	1	162.59	1	288.23	1
131,072	38,240	59.69	1.00	84.09	0.97	143.78	0.98
262,144	19,120	30.02	1.00	43.24	0.94	73.26	0.96
294,912	16,995	26.71	1.00	39.15	0.92	65.86	0.95

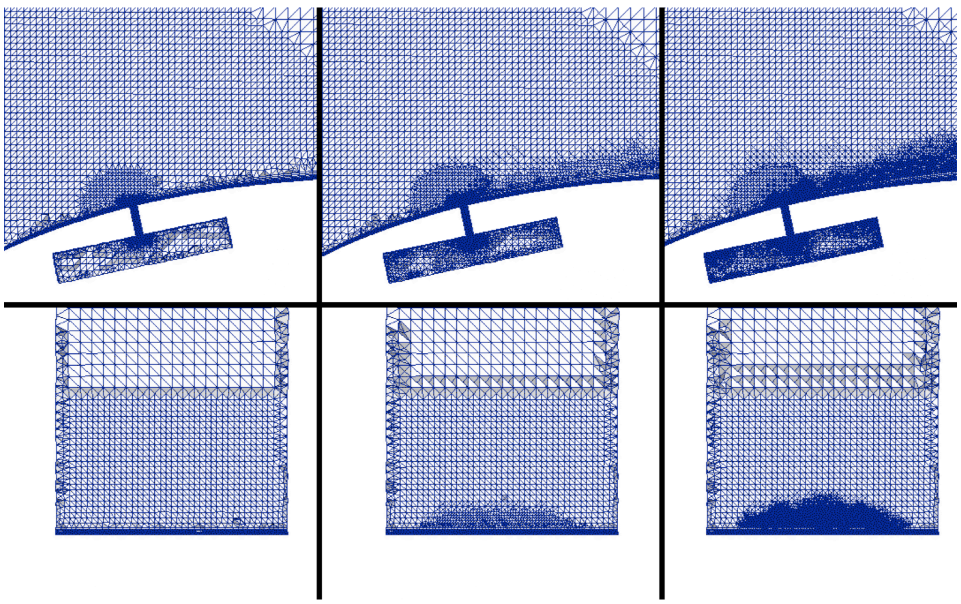
without IPMod strong scaling factor is
0.88 *(time is 70.5 secs),*
for production runs savings can be in ***43 cpu-years***

Finite-span synthetic jets

CAD geometry used in CFD matches experiment

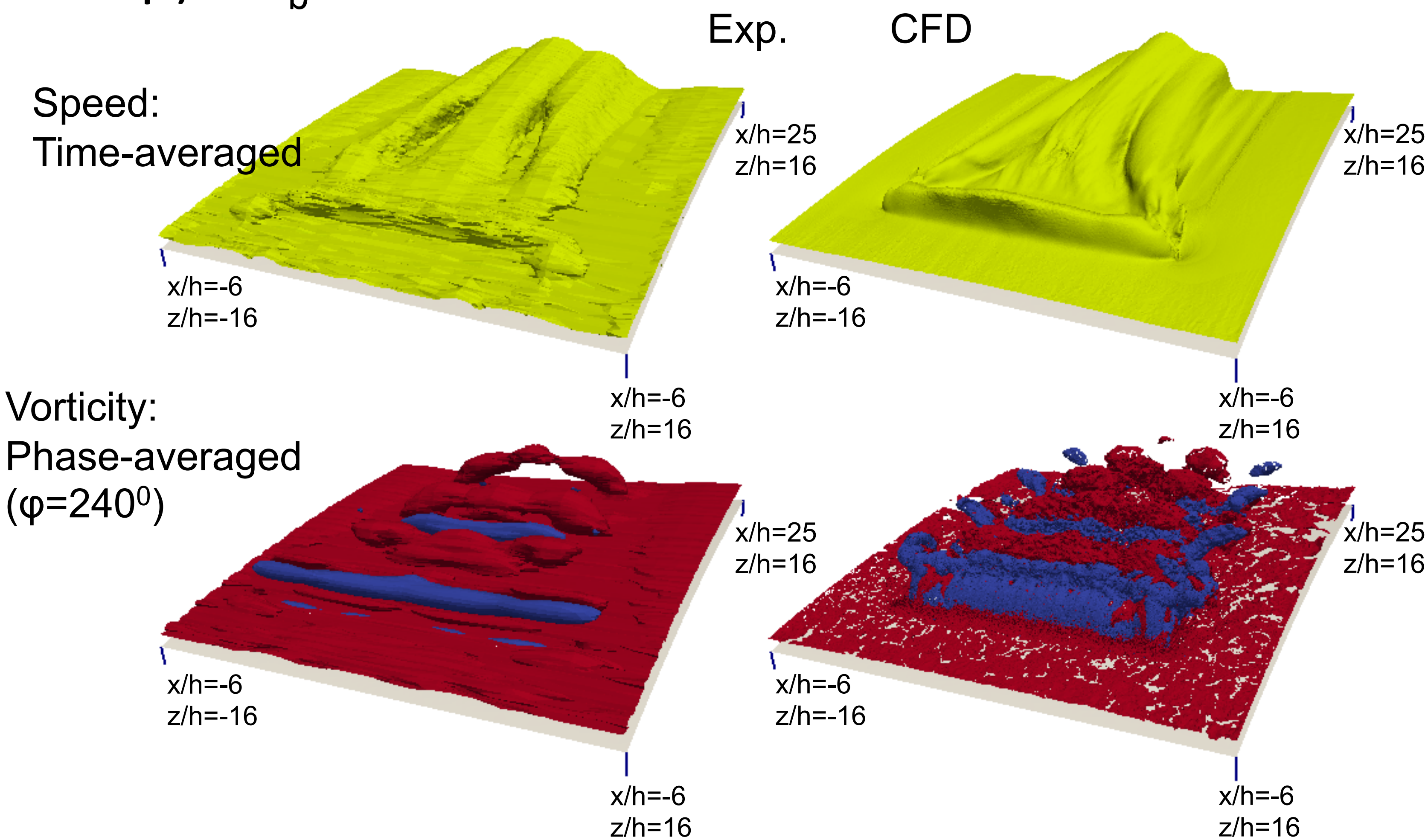


Initial and 2 cycles of adapted mesh
Spanwise slice (top)
Streamwise slice 20 slit widths down stream (bottom)

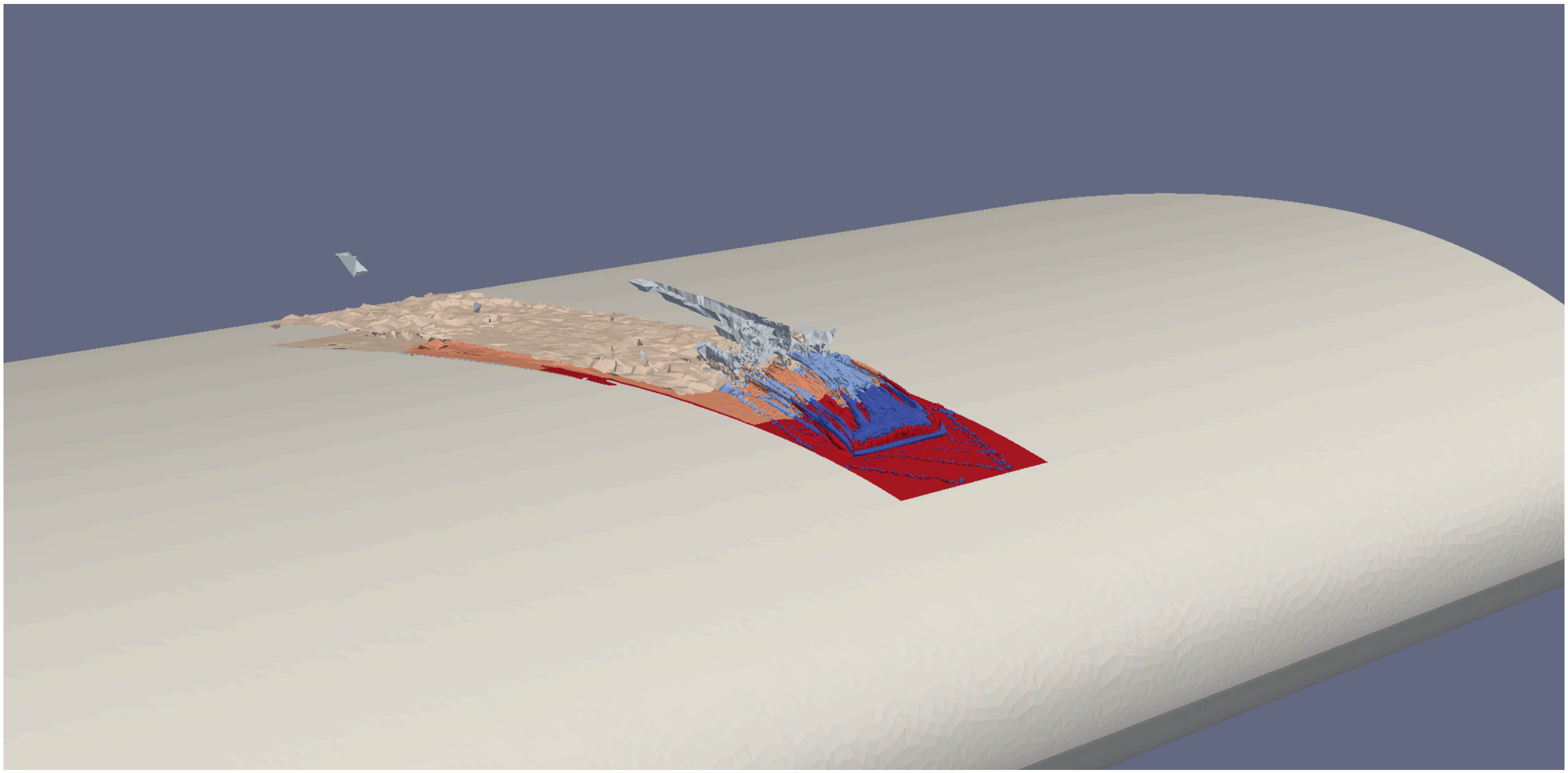


Time-averaged Aeroshaping Captured

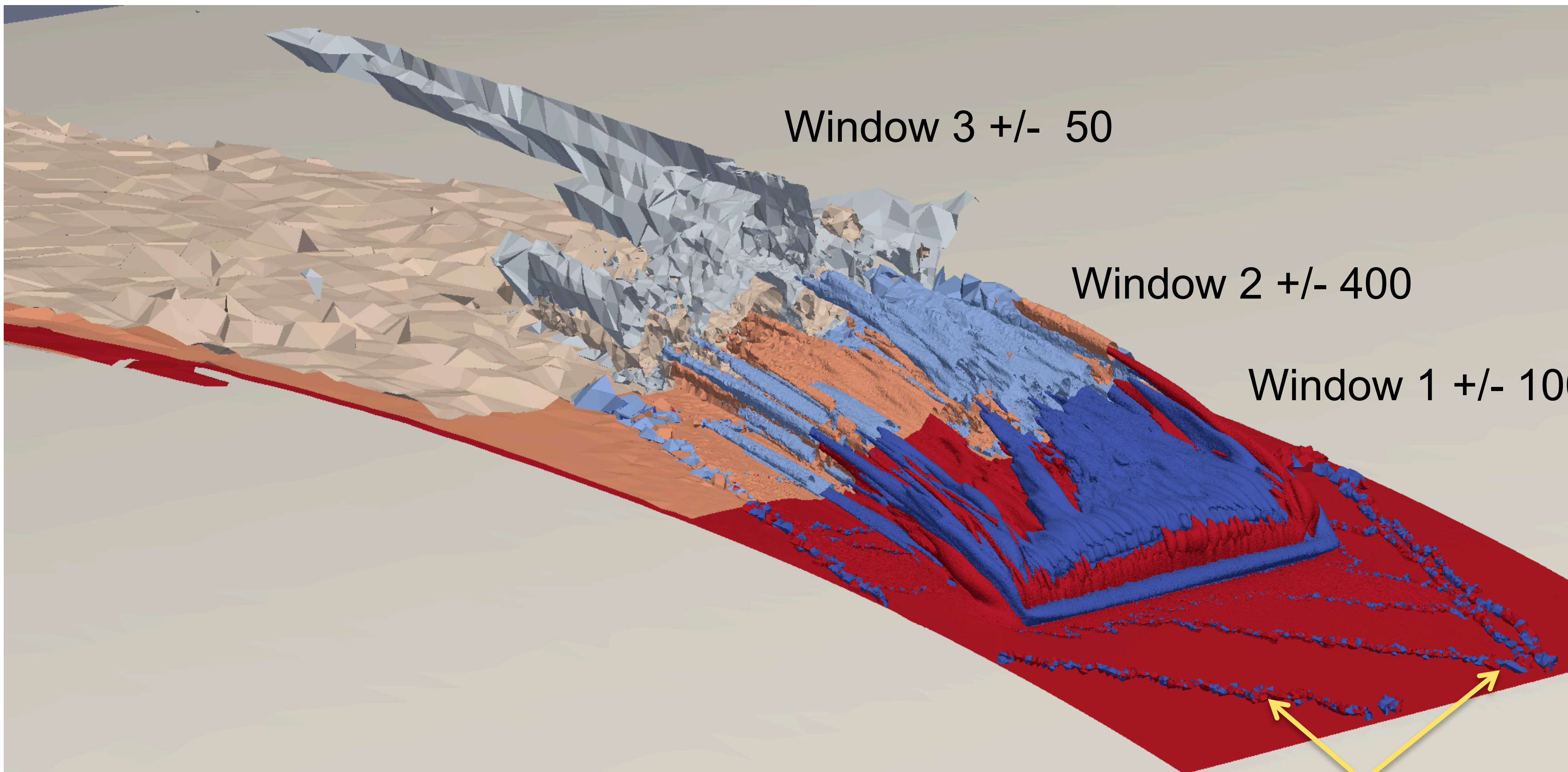
- Comparison between experiments and CFD – high C_b (or $C\mu$) – C_b=1.2



Full Swept Wing: Graduated Vorticity

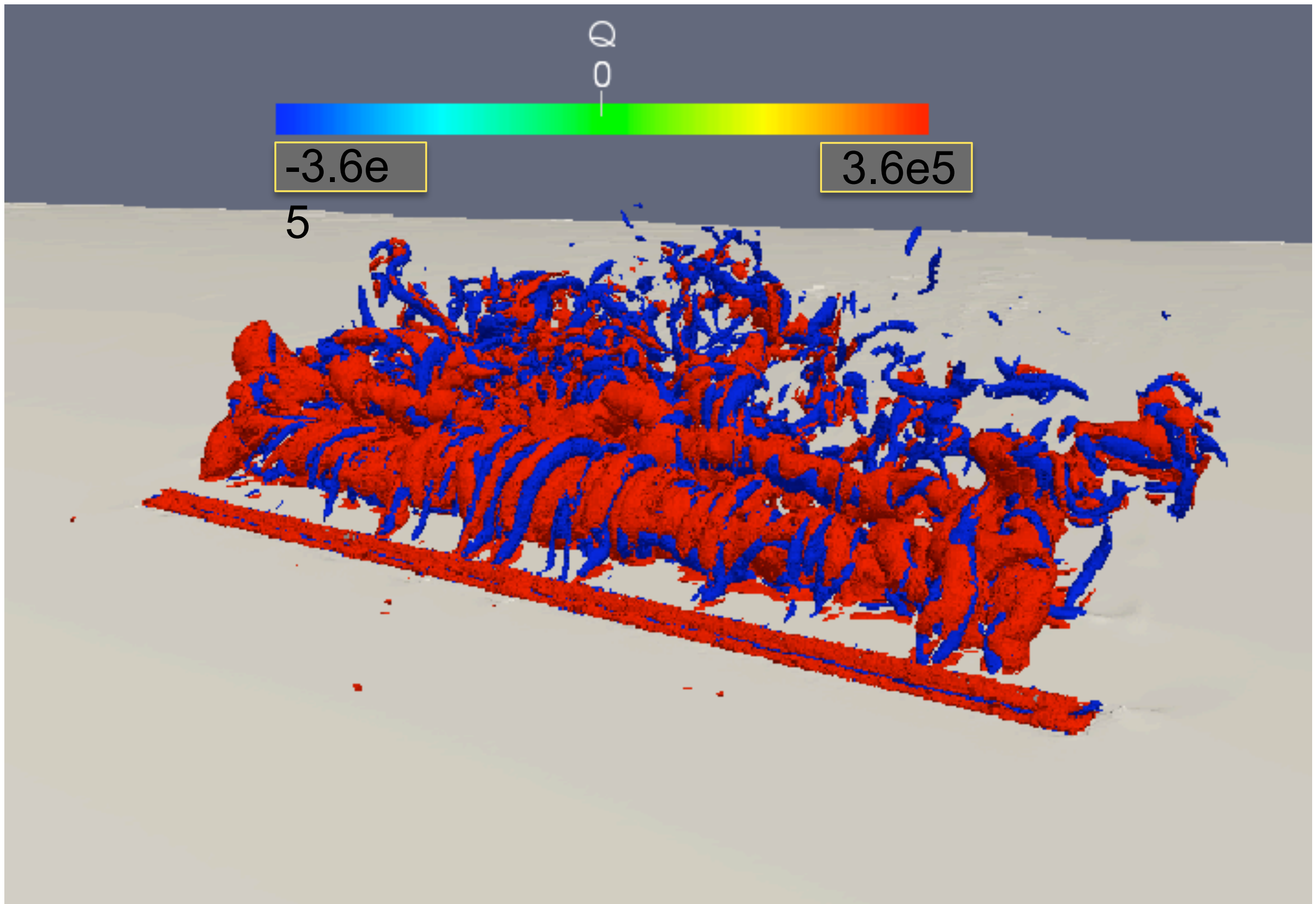


CFD Time Averaged/Graduated Streamwise Vorticity



Artifacts of parallel viz

Instantaneous Isosurface of Vorticity



Flow Control Simulation: Scientific/ Engineering Value

- Simultaneous, precisely matched experiments is challenging, and requires iteration to validate CFD for flow control
- Once validated, simulations provide detailed field data to understand flow structures that are most effective for controlling the flow.
- Open and closed loop controls are being integrated with the CFD to explore design of new flow control actuators and optimal sensor placement.
- Future applications in wind turbines looks very promising as synthetic jets can increase or decrease lift to offset gust=> reduce turbine blade unsteadyness => gear boxes last longer=> wind turbines more robust=> competitive.
- Wind turbine simulation is also being coupled to atmospheric models not only to capture gust effects but also wind turbines impact on atmospheric flow and ultimately climate.

Conclusions

- Complex geometry/physics=> Real world Apps
- Implicit solvers: Complexity ⇧ but n_{step} ⇩
- Excellent scaling results
- Big Science AND FAST SCIENCE
- Anisotropic Adaptivity brings real geometry problems into reach of solution in a USEFUL time frame
- Multiphase simulation capable of modeling turbulent flow with mixture of steam and water
- Complex geometry of very small flow control devices being simulated and validated

- Thanks